2.5D Printing: The Evolution of the Water Lily

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Abstract

This paper considers 2.5D printing in a number of ways: by exploring the relationship between textural appearance of objects as seen in the real world and how these are interpreted by artists and rendered as paintings and drawings. This is significant in order to gain deeper insights into the appearance of texture in both real-world and computer-based image processing.

Secondly as a practical understanding and development of methods for the application of texture or 2.5D printing, in which the authors have worked on the development of algorithms that can translate pictorial statements as reproducible textured images. It departs from halftoning methods (dots, pixels, pattern screens), and presents vector based (non-photographic rendering methods and autographic) methods for image generation. We also present recent developments on the application of vector driven methods to drive brushes, pens and other artists' tools to create reproducible artworks.

Introduction

This paper reflects on the development of texture and colour printing, by exploring the relationship between on screen images, development of colour separation algorithms, and computer aided methods for applying paint to paper. This research departs from traditional methods of colour separation and printing methods, as it incorporates an extra half dimension or 2.5D printing. 2.5D printing relates to emerging interests in the technical, creative and physical approaches to capturing, modelling and the application of textured marks that emulate the textured appearance of materials. The focus here is within a digital context and the opportunities to render colour and texture information as a combined printing method to create a complex pictorial composition. We use the term *combined*, as the emphasis here is to apply colour and texture at the same time, and not a printed texture upon which a halftone over-coat is applied.

The primary questions are:

- what are the essential characteristics of real-life texture, and how can these qualities be transcribed into a synthetic world?
- what are artists' understanding of materials and textural qualities, and their ability to transcribe their percept into two dimensions e.g. painting and drawing?
- how can physical artworks be created that incorporate both analogue (paint, ink, graphite) and digital (vector) be created that could be described as containing textural or 2.5D qualities?

In order to establish a robust working methodology, and as we have continued to explore the subject in greater depth, we have found that 2.5D printing has proven to be highly complex, but an enthralling subject. And, in seeking a definition as to what are the significant qualities of 2.5D printing we have looked across a wide range of disciplines including perception, camouflage, art history, design, archaeology and conservation. We have considered the pictorial representation of objects and landscapes, in particular, investigation of painting, drawing and composition methods by artists to ensure pictorial representations of the world are convincing [1]

As part of our methodology, we have developed different methods to achieve a range of rendering outputs, for example a global algorithm that simulates the use of the same brushstroke might resemble a pointillist effect, or a more localised method, whereby brush lengths and stroke widths can be modified according the content of the image (see section on methodology). In order to do this, it has required a return to the basics of pictorial composition, for example, how scenes are conceived and translated as pictorial representations, and whether these representations are convincing. Furthermore, whilst the term 2.5D is contemporary and reflects a quantitative engagement, other terms in the lexicon such as relief, impasto, degrees of projection, embossing, intaglio, texture, roughness, (and more) are alternative ways of describing the perceptual surface qualities of an object. It is these qualities that are harder to define. And yet, artists and craftspeople have been engaged in the physical relationship of material, process and capturing the textural qualities of objects for centuries.

The novelty here is that the artist can make multiples of the same image, try different colour-ways or develop variations – as one would proof a print. The difference here is that whilst the process is digitally driven and colours are machine applied, it uses analogue methods and materials to print the image and attempts to emulate the gestural marks of the artist to create a more dynamic composition.

Figure 1. The water lily – the original source file for testing a range of painterly outputs.

The title of this paper refers to the first trial image used for this project. Over the last year the water lily (figure 1) has undergone a wide range of artistic interpretations. It has helped us understand the relationship of tools, brush marks and direction of brush strokes in relation to gesture. It has also helped us to understand the necessary components in reading the subjective or semantic composition of an image. This paper is complementary to a second paper in this session at Electronic Imaging, which provides a more technical analysis of the spatial segmentation process of the image. (Vector Driven 2.5D Printing with Non-Photorealistic Rendering) [2]

The appearance of texture

Texture is an important visual attribute that enables us to perceive our surroundings: it enables us to distinguish the differences between materials (substances or substance out of which a thing is or is made), identify the structure and shape of objects, and discriminate edges in a complex pictorial scene. In order to gain an understanding of creating a verisimilitude of materials we can study lighting techniques, drawing and painting techniques used by artists and historians [3, 4, 5, 6, 7] along-side scientists working on human vision, colour and texture perception [8, 9, 10].

Surface modelling effects have evolved from limited algorithms to describe limited reflective, smooth surfaces [11] in the 70s, to highly complex organic, asymmetric, animated materials. All these variables require an incredible amount of processing and methods are being sought to reduce resolution through down-sampling, and based on the photographic methods of antialiasing. [12] The complexity in the creation of a natural textural render (both in virtual and as physical objects) is essentially due to the enormous range of components that are required to incorporate all the nuances of a texture such as colour, fibre, grain, reflectance, specularity, weave, hardness, softness, glossiness, fluidity.

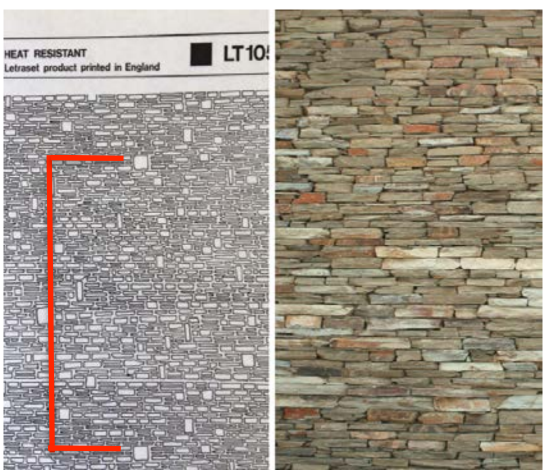

Figure 2. Sample image of a wall pattern. The red lines indicate the repeat pattern. Right: an irregular pattern of a drystone wall.

As demonstrated in figure 2, our HVS is able to pick-out repeated elements, for example, a wallpaper print of a brick wall and a real-world brick wall, one can discriminate the difference between natural and patterned texture, and incorrectly rendered surfaces can challenge levels of acceptability. [13] Furthermore to render surfaces with no discernable pattern structure that comprises unlimited variations can result, as demonstrated by the computer-generated rendering, in exceptionally large file sizes.

Image rendering approaches of coloured images

In order to gain understanding of image composition, the authors observed the brush strokes of painters. Inspired by the meticulous painting methods by artists including Jan van Eyck (1390-1441), Diego Velázquez (1599-1660), Vincent van Gogh (1853-90) and Georges Seurat (1859-91), we looked at the use of lines, modulation of similar strokes, and repetitive over layering of paint. [14]

Figure 3. Vincent van Gogh, Olive Grove (1889) Oil on Canvas. Van Gogh Museum, Amsterdam

The objective for the 2.5D painting project is to create a vector-driven painting machine that applies a brush loaded with paint, or a nib with ink to paper in a methodical and mechanical way, yet remain non uniform and human analogous. The important distinction is not to replace halftone dots by halftone strokes, but to create brush-strokes that demonstrate the texture direction of the objects, discriminate edges in a complex pictorial scene. For example, van Gogh used a similar repeated element in the painting *Olive Grove* (1889), but changed the depth of field by modifying the size, the direction and the colour of the element. This is particularly apparent in the diagonal brushstrokes that describe the receding and undulating mound at the foot of the trees (figure 3).

Figure 4. Diego Velázquez, Juan Francisco de Pimentel (1684) detail, oil on canvas, Prado Madrid.

A second important aspect of the image segmentation process is the ability to distinguish the differences between materials and study lighting techniques using colours, tools and mediums in relation to the object or scene that is being drawn. For example, Velázquez used different brushes, broader gestural approaches to describe the background of an object and small brushes to pick out the detail and the highlights (figure 4).

We consider strokes as analogous to vectors, representing a series of movements with magnitudes and directions. Our objective is not to render the illusion of painterly styles with pixels. Rather we explore the operation of print apparatus for the tangible production of texture, which originate in painterly styles. This is comparable to the concept of the texton [15] as a way of describing the individual structural characteristics of a texture. He identified a list of image features including: size, orientation, line terminations and line crossings. A brushstroke texton method has also been explored, which creates a representation of the different brushworks in a painting [16] as well as 3D textons in relation to appearance of materials [17]

In our background search for an identification of what are the basic constituents to identify, classify and reproduce texture, interesting early research undertaken by Marr differentiated between image and representation, and the use of what he described as primitives to describe an object's shape. [18] He suggested there are two primary classes of shape primitive: surface based (2D) and volumetric (3D) volumetric primitives involve the spatial distribution of a shape and vectors to describe its dimensions, along with shading and texture gradients. More recently, Landy and Klatzky identified appropriate methods for texture reproduction, whereby the three main characteristics in determining the qualities of a surface texture are: value, repetition and edges. [19, 20]

From a perceptual point of view, V.S Ramachandran in describing the range of signals from the brain when looking at art, [8] provides ten qualities that contribute to his law of aesthetics (an area that Semir Zeki calls neuro-aesthetics), the most important being 'grouping' (patterning), 'peak shift' (essential characteristics), 'contrast' (edges, boundaries). These are similar to Joseph Hawkins' psychological observations, who writing in the 1970s, in his introduction on 'Textural Properties for Pattern Recognition' identified the three main characteristics for determining the qualities of texture: value, repetition and edges. [13]

Computational approaches using stroke based rendering

Non-photorealistic rendering (NPR) uses computational methods to interpret digital formats (captured visual scenes or original works) and renders them with an alternate artistic expression. Typical source formats are pixel based images, although NPR can also be derived from 3D models and determined algorithmically without a prior source. The utility in NPR can be functional, for instance 'unrealistic' shading schemes aid in the visualisation of complex parts drawn in computer-aided design. [21] The utility of NPR can also be to provide a purely artistic interpretation from a source, or to provide interactive software tools to aid in the creation of stylised digital art works.

Stroke based rendering methods (SBR) is a subset of non-photographic rendering processes, that places strokes of paint instead of dots. Depending on the complexity of the stroke, the brush stroke range from the simplest such as a stipple to a more complex stroke that emulates a painterly style. Hertzmann provides an overview of a range of rendering effects [22] and Hegde [23] concentrates more on painterly strokes. Other authors have explored specific styles, such as impressionism by Kasao [24], and Yang, [25], oriental ink painting by Ning, 26 and Cheok, [27], or pen-and-ink illustration by Winkenbach, [28]. In this way SBR is motivated to model characteristics of effectors (i.e. a horsehair brush), mediums (i.e. watercolour) and substrates (i.e. canvas) to synthesise a convincing screen based render, for example by Curtis, [29]

The methodology is described in more detail by O'Dowd (2015). The following figure provides an overview of the segmentation process.

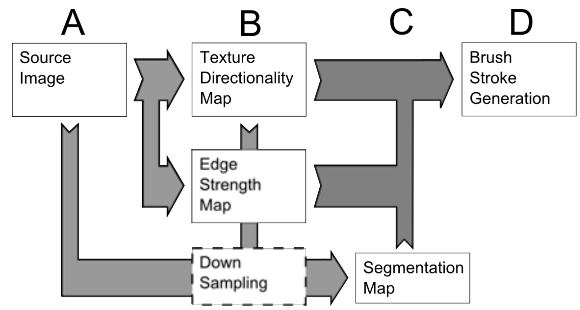

Figure 5. An overview of the brush stroke generation process. At (A) a digital image as a colour refence and pixel position, (B) an image convolution and colour difference are used to derive texture directionality and relative edge strength, (C) colour information, edge strength and texture directionality are used to generate a spatial segmentation of the source image - an optional down sampling process may discard information from A and B prior to segmentation, (D) information at steps B and C inform the generation of brush strokes to print.

Our approach to image segmentation methods of coloured images into stroke based rendering has considered two different image-making routes:

Auto-segmentation – where bitmap based images (bit-for-bit, raster graphics, pixels, points, image, jpeg) such as photos, screengrabs, iPad art can be converted to vectors. The algorithm automatically separates the image into coloured layers. The layers are determined by: edge strength, texture direction, x/y pixel adjacency, hue/saturation/ brightness. This approach is inspired by the *Non-photorealistic rendering* algorithms for texture directionality described by Kasao et al through several papers [24, 30, 31]

Autographic – where vector based graphics (paths, points, handles, anchors, Bézier curves, smooth lines) such as AutoCad Illustrator, Freehand, can be exported as vector based images (line work, x-y-z, postscript, svg, animation). Layers, brush dimensions and lengths, characterisation of brush strokes can be maintained and used to drive the painting machine. This approach is inspired by Direct Write printing processes [32, 33]

Development of painting machines and programme interface

As part of our practical printing output, we adapted plotters, and more recently constructed our own painting/drawing rigs. These painting machines have undergone various iterations and refinements. We began by hacking a vinyl-cutting plotter and replaced the cutting head for a paintbrush holder.

A second machine, a low cost wood router kit with 3 degrees of freedom (x, y and z) was modified to carry a paintbrush and other deposition tools. The machine has a printable area of 310mm by 260mm and a range of 40mm vertically. The machine is built from an extruded aluminium frame and NEMA17 stepper motors drive the x-y and the z axis. Variations include methods to load the brush with paint, such as a paint pot-holder that could rotate underneath the brush and rotate away to enable excess paint to be removed as the brush is drawn up.

RepRap 3D printer electronics operate the hardware, and was selected for the potential to expand on input and output control versus standard CNC electronics. The machine therefore accepts the GCode protocol to determine movements and speed of operation. Currently the machine does not have any sensors other than mechanical switches to home the coordinate system. The machine does not have automated colour changing or a continuous loading mechanism for the brush. Instead colours are mixed by hand, from which the printer is programmed to return to the pot location and reload the brush after a number of applied strokes.

The third generation machine has a printable area of approximately 1.3 x 1.3 metres, again constructed to our specification. It comfortably takes an A0 sheet of paper and enables us to make much larger gestural paintings.

Of course, there are many examples of painting machines to produce art in more human analogous ways. Lindemeier includes a review of early painting machines and related artists 'eDavid' [34] 'Paul' Tresset, [35] and a humanoid robot [36] are painting machines that demonstrate a closer approximate to human movement. However, our contribution here is the combination of key components: the variety of input (own digitally generated as SVG, artwork, photo), the ability to modify images (auto-segmentation process and autographic methods), the ability to input and output as vectorial coordinates, the use of a variety of tools (paints, pens, nibs), and mediums (oil, acrylic, ink, watercolour) to output the image, and, the ability to create textured and scalable artworks onto a range of substrates.

Auto-segmentation process

For this paper, we will describe the *auto-segmentation* approach, which allows the program to convert the pixels in a picture/photograph into vector paths that can be used to drive a paintbrush or pen on the printing machine. Although the program performs most of the segmenting, the user can manually adjust many different settings to achieve the desired printed output (figure 6).

A description of the setting for the manual modification of vectors

Texture Smoothing – as the following figure illustrates, reduces the complexity of vector direction in the image, resulting in a decrease in texture noise.

Min Width – describes the minimum width of the stroke, which emulates the size of the paintbrush that will be used in the painting machine. For example, if a high degree of fine detail is required, the number is set to low and a fine brush is used. If a thicker brush is required, set this high (measurements in mm).

Max Width (Layer) – describes the maximum possible width of the stroke, encapsulating the spread of bristles, permitting variation in width across the length of a single stroke. This specifies the width per layer, and will automatically set itself to the maximum width available when brush strokes are generated by the software.

Max Width (global) – Allows the user to set the maximum desirable width of stroke for all layers. Each layer may not attain the maximum width, which can be inspected via Max Width (layer).

Max Length (Layer) – describes the maximum length of the brush stroke per layer. This can also be changed for each layer of the print, but will be automatically updated to represent the longest stroke in the layer after stroke generation. Longer brush strokes suit a certain style of print, for a pointillist style then select a short stroke length (measurements in mm).

Max Length (global) - Allows the user to set the maximum desirable length of stroke for all layers. Each layer may not attain the maximum length, which can be inspected via Max Length (layer)..

Bleed – The program default setting will prevent each layer of colour from overlapping. However, by adjusting the bleed of the layers, the density of the stroke can be modified by increasing the bleed, and thus forcing the layers and colours to overlap. This changes the appearance of the image to create a more gestural effect that might be more appropriate for a watercolour painting, as opposed to a more hard edge graphic effect by maintaining edge definition

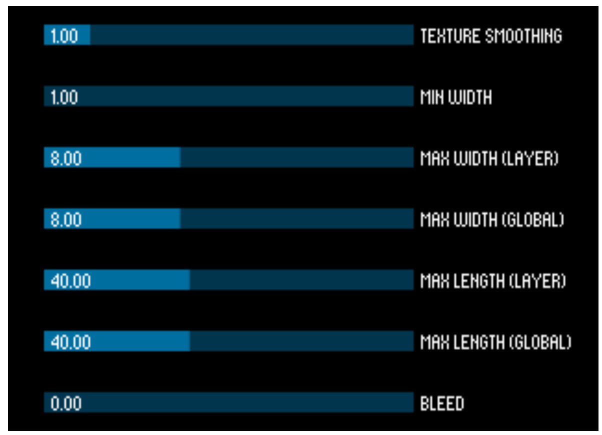

Figure 6. Slider bars in the vector programme to manually adjust the output.

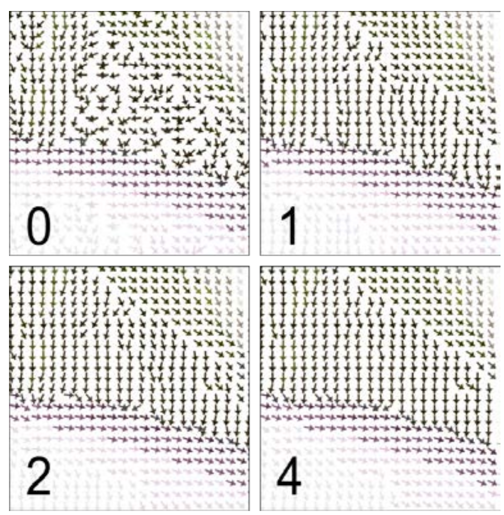

Figure 7. Illustrates how by increasing the texture smoothing setting from 0 to 4, can reduce the complexity of vector direction.

A description of the settings for manual segmentation of the image

X Gain, Y Gain, Edge Gain, Texture Gain, Hue Gain, Saturation Gain and Brightness Gain each attenuate the segmentation algorithm. Setting a gain value to zero removes the related character of the image pixel from the segmentation operation. The above figure shows little regard for pixel position in the image, high regard for edge and texture, and a dominating preference for colour. These are described in detail in [2].

A description of the setting for pen-up and down

The Pen Up and Pen Down setting determines the highest and lowest position of the brush in the physical Z axis. This has a direct relationship to the Minimum Width and Maximum Width of stroke set by the user.

The Pen Up position should be set so the brush bristles achieve the desired minimum width of stroke on the substrate. Pen Down is set to cause the displacement of bristles to match the desired Maximum Width of stroke. The software automatically creates variation in the Z axis along the line of a stroke. The stroke generation algorithm pursues the widest possible stroke at each point along the path, but is constrained by the occlusion of prior strokes and the boarders of segmentation regions. These constraints are attenuated by the 'bleed' and 'overrun' parameters.

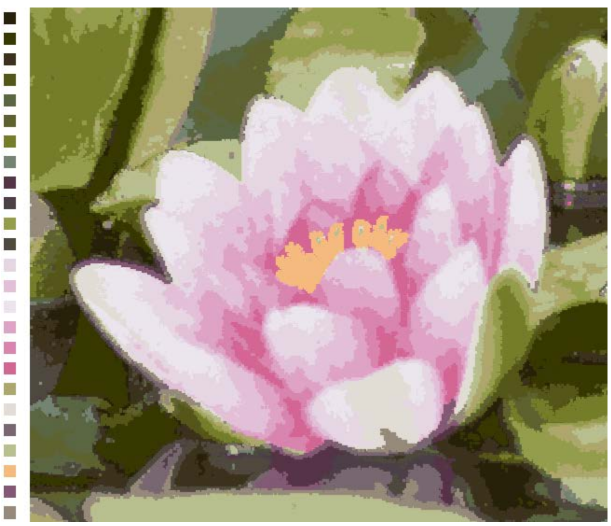

Figure 8. Segmentation of the image showing 25 layers and colour swatches on the left.

A description of the painting outputs

The following figures demonstrate the painting evolution of the water lily and the studies created on the 2.5D printer. These images reflect our empirical understandings to mediums, tools, and development of software algorithms according to the increasing variables and complexity of the image composition.

As demonstrated in the following figures, these are grouped according to chronological evolution. The first grouping (figures 9-11) addresses the directionality of brushstrokes, for example, by changing the vector direction, the stroke width and density of the width, highlights the difference between a more organic asymmetrical appearance of the water lily versus the horizontal and vertical strokes in figure 9. The colours, strokes and segmentation are very primitive. Here we were testing the mechanisms of the machine rather than the finer painterly qualities of creating a flower.

Figure 9. Oil painting, large flat brush, simple colour segmentation and brush stroke direction

Figure 10. Oil painting, large flat brush, modification of brush stroke direction and increase of strokes

Figure 11. Acrylic painting, large flat brush for background medium brush for foreground, modification of brush stroke direction and increase of strokes

However in the following three figures 12-14, demonstrate some finer sensibilities to the subject, smaller brush strokes are used, alongside a much more gestural approach to the painting that incorporates different colour versions and the fluid qualities of a water colour medium. The paints in figures 12 - 14, are applied wet on wet, which has resulted in the mixing of the paints on the paper.

Figure 12. Small acrylic version 1

Figure 13. Small acrylic version 2

Figure 14. Small watercolour

The following figures demonstrate how by changing the character of the stroke, can affect the final appearance of the painting. In figures 15 and 16, a medium stroke length - that is fatter and wider - is globally applied. Likewise, a medium sized brush is used to paint the images, thus creating the appearance of a 'painting by numbers' quality.

Figure 15. Acrylic painting, medium brush for background and foreground, modification of brush stroke direction and increase of strokes

Figure 16. Acrylic painting, medium brush for background and foreground, modification of brush stroke direction and increase of strokes.

Figure 17. Acrylic painting, fine brush for background and foreground, modification of brush stroke direction and increase of colours and strokes.

In figures 17 and 18 a finer brush length and width is used, resulting in more space around the brushstrokes. The brush strokes in 17 and 18 are longer, thereby creating more of a definition to the edges and shading of the petals and a greater level of dynamic expression.

Figure 18. Acrylic painting, fine brush for background and foreground, modification of brush stroke direction and increase of colours and strokes.

Figure 19. Example of alternative materials used, such as felt-tipped pen (25 layers)

Figure 20. Example of alternative materials used, such as water-colour (25 layers)

The brush strokes in 19 and 20 are longer, thereby creating more of a curve like definition in the shading and the petals and a greater level of expression. Furthermore different mediums and materials were used.

Conclusions

This project has addressed 2.5D printing methods with the aim to gain deeper insights into the appearance of texture in both real-world and computer-based image processing, by documenting the relationship of textured appearance of objects as seen in the real world and how these are interpreted by artists and rendered as paintings and drawings. Secondly it has developed methods to translate pictorial statements into graphical coding that can be used to created reproducible textured images. Thirdly it has looked at the relationship between the artisan, their tools and the fluid dynamics of paint and how these centuries old processes can inform mechanical interfaces for driving a painting machine. The end result is not to replace artists by painting machines, but to explore a more meaningful interaction between marks made on a tablet or screen and how these can be transcribed using real materials and tools.

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